MAKING DESIGN DECISIONS USING CHOOSING BY ADVANTAGES

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ABSTRACT

Choosing By Advantages (CBA) is a sound system to make decisions using well-defined vocabulary to ensure clarity and transparency in the decision-making process. Making sound design decisions aids in successful implementation of set-based design. This paper explores the use of CBA to select a design for steel reinforcement, aka. rebar, in a beam-column joint. CBA, in conjunction with set-based design, allows the engineer to explicitly consider multiple design alternatives that meet various 'must' and 'want' criteria. The factors and criteria developed to evaluate the design alternatives reflect the values of the various project team members involved in rebar design and construction. Because decision-making *is* subjective, it is important to document *why* and *on what basis* decisions are made so they can be revisited at a later time on that project, should new considerations or facts become available, and on future projects. Decision-makers using CBA list the attributes and advantages (the beneficial difference between two alternatives) of each alternative and then assign a degree of importance to each advantage relative to the one that is least preferred. The example presented herein shows that team member values may conflict, but including all perspectives in the CBA table enriches the decision-making process and cultivates a shared understanding among project team members.

KEY WORDS

Choosing By Advantages, group decision making, set-based design, reinforced concrete design.

INTRODUCTION

When designing a reinforced concrete structure, beam-column joints may require extra attention, as they tend to be congested (i.e., rebar in the joint is very dense). As such, choosing rebar for beams and columns intersecting at a joint can be a challenging task. Structural engineers tend to design reinforcement for a beam separately from that for a column then check their compatibility. The American Concrete Institute (ACI) mandates compatibility checks, including development length for the beam rebar, area ratio of rebar compared to concrete in the joint, and rebar diameter requirements. However, ACI does not impose any constructability requirements, so code-compliant joints may be difficult to build. Rebar fabricators

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and placers, in fact, may find code-compliant designs far from satisfactory. CBA allows such project team members to have an input in the selection from alternative designs. This paper presents an example of CBA used to select rebar for a beam-column joint. Parrish (2009, pp. 136-164) provides more detail about this example.

RELATED WORK

The authors explored decision-making processes that could support group decision-making necessary for evaluating alternatives developed in set-based design. Saaty (1990) developed the Analytic Hierarchy Process (AHP) for decision-making, which makes use of pair-wise comparisons of criteria. Thurston (1990; 2006) explains Multi-attribute Utility Theory in the context of engineering decision-making, which involves assigning preference to multiple attributes and combining these preferences (via weighted averages) to determine the most-preferred alternative. Ullman (2001) explains Robust Decision-making, a system that focuses on making decisions given incomplete information. Suhr (1999) developed the Choosing By Advantages Decisionmaking System (CBA), a system that considers advantages of alternatives and makes comparisons based on these advantages, presented herein.

CBA defines a vocabulary for use in the decision-making process, and CBA practitioners and trainers insist on its consistent use to make sure all people involved in the decision-making process are "speaking the same language"—a necessary prerequisite for sound decision-making. CBA defines the terms alternative, factor, criterion, attribute, advantage, and importance of an advantage. An alternative is a possible decision (e.g., choose alternative 1 or alternative 2). A factor is a container for criteria, attributes, advantages, importance, and other types of data (Suhr 1999, p. 15). A criterion is a decision rule or guideline established by the decision-maker(s). A criterion may be a 'must' criterion, representing conditions each alternative must satisfy, or a 'want' criterion, representing preferences of one or multiple decision-makers. CBA considers cost separately from other factors, and does not treat it as a criterion. An attribute is "a characteristic, quality, or consequence of *one* alternative." An advantage is a beneficial difference between *two* and only *two* attributes. Only advantages are expressed in the CBA system, i.e., a disadvantage of one alternative is listed as an advantage of another.

CBA is a decision-making system that includes methods for virtually all types of decisions, from very simple to very complex. This paper presents the Tabular Method, used for moderately complex decisions. For moderately complex decisions, like the one presented here, the CBA process consists of five phases: (1) the Stage-Setting Phase, (2) the Innovation Phase, (3) the Decisionmaking Phase, (4) the Reconsideration Phase, and (5) the Implementation Phase. The third phase is the primary subject of Suhr's 1999 book, *The Choosing By Advantages Decisionmaking System.* In the Tabular Method, Phase 3 comprises four steps: (1) Summarize the attributes of each alternative, (2) Determine the advantages of each alternative, (3) Assign a degree of importance to each advantage, and (4) Choose the alternative with the greatest total importance of advantages.

CBA anchors decisions to relevant facts and postpones value judgment about alternatives until the last responsible moment (Poppendieck 2000), when failing to make a decision eliminates an alternative. Project team members try to keep the set of alternatives considered as broad as possible at the outset of the decision-making process. Team members can develop multiple factors with different 'want' criteria to postpone making value judgments about alternatives until later in the decision-making process. Summarizing attributes consists of listing facts or data about each alternative, thus anchoring the decision to that data. Attributes are inherent to an alternative, so summarizing them does not involve subjective judgment. Determining the advantages of each alternative does not require subjective judgment itself, though advantages may depend on the 'want' criteria in a given factor, which are subjective. Assigning a degree of importance to each advantage is the first task that requires decision-makers to make value judgment about alternatives, and CBA postpones it as long as possible.

CBA has been used for group decision-making by the National Park Service (Suhr 2009), choosing a home (Adams 2003), for selecting a green roof (Grant 2007), and for design and construction decision-making (Parrish et al. 2009).

EXAMPLE: DEVELOPING A SET OF BEAM-COLUMN JOINT ALTERNATIVES

Figure 1 shows the rebar area requirements for Beam B and Column C, which intersect at a joint in a reinforced concrete frame. It lists the required area of rebar for each member. To begin, the structural engineer applies a "divide and conquer" methodology, designing the beam and column reinforcement separately, to determine sets of possible beams and columns. This example explores two of the reinforced concrete frame design spaces: one for the reinforcement of the beam and one for the reinforcement of the column. Other dimensions of the design space (not explored here) include beam and column dimensions, concrete strength, aggregate size, and others.

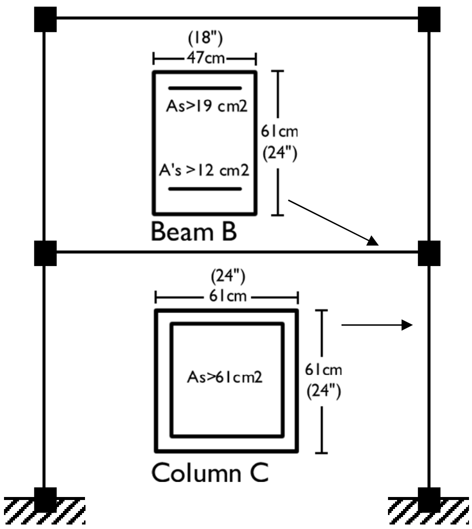

Figure 1: Canonical Example of Reinforced Concrete Frame with Beam B and Column C (Parrish et al. 2007)

During the Innovation Phase of the CBA process, 'must' criteria rule out the unacceptable alternatives. The ACI-318 structural concrete code (ACI 2005), defines 'must' criteria for the minimum area of tension steel, A_s (top of the beam), and compression steel, A_s' (bottom of the beam), necessary to achieve the required beam or column flexural strength. In this example, the beam is 47 cm by 61 cm, which requires $A_s > 19.35\ cm^2$ and $A_s' > 11.61\ cm^2$. Similarly, the minimum required steel area for the column is determined to be $A_s > 61.29\ cm^2$. ACI-318 further limits the reinforcement ratio, ρ (a ratio of rebar area to concrete area for a given cross section) to a maximum of 0.025 to ensure ductile section behaviour.

After the structural engineer calculates necessary rebar areas, (s)he works with other project team members to define sets of design alternatives for Beam B and Column C. The set of possible designs is large in this case as many reinforcement configurations would meet the rebar area requirements. This example does not show every possible reinforcement alternative. Figure 2 shows a representative sampling of the set of design alternatives for Beam B, including beams reinforced with different bar sizes, as well as different bar configurations (i.e., one or two layers of rebar). Likewise, Figure 3 shows design alternatives for Column C, each reinforced with different bar sizes. Other alternatives include reinforcing the beam or column with smaller rebar (#16 [US #5] and #19 [US #6]) or more bars of the sizes shown, as discussed in Parrish (2009, p. 143).

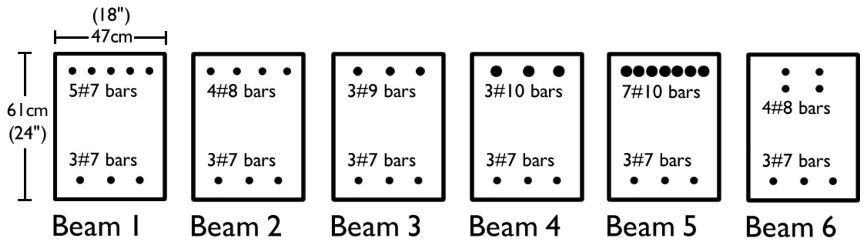

Figure 2: Sampling of the Design Space for Beam B (Figure 4 in Parrish et al. 2007)

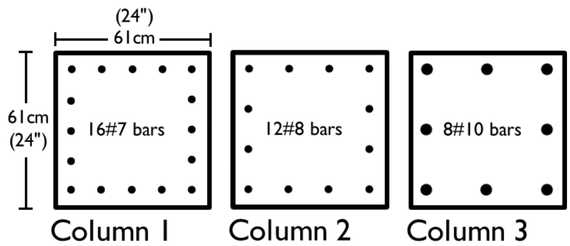

Figure 3: Sampling of the Design Space for Column C (Figure 5 in Parrish et al. 2007)

SELECTING BEAM-COLUMN ALTERNATIVES

Selecting a beam or column alternative is an example of a decision involving mutually-exclusive alternatives with equal dollars (Suhr 1999). Should the alternatives considered here have different costs, the difference is assumed to be marginal, so costs will not be addressed in the selection process.

Six alternative beam-column joints are selected from the set of six beams (Figure 2) and three columns (Figure 3). Clear spacing requirements between the beam and column reinforcement eliminate Beam 1. Beam 4, Beam 5, and Column 3 are reinforced with #32 [US #10] bars (bars with a 32.26 mm diameter). ACI-352 mandates bar diameters be less than or equal to 30.48 mm (ACI 2002); this 'must' criterion eliminates Beam 4, Beam 5, and Column 3 from consideration. Thus, Beams 2, 3, and 6 and Columns 1 and 2 remain in consideration.

DETERMINING FACTORS AND CRITERIA

Once decision-makers have developed alternatives, they can compare them using the Tabular Method of CBA. Table 1 shows the CBA table for the six beam-column joints considered. The left-hand column lists factors and criteria. Which factors are considered depends on the decision-makers' ability to discern unique advantages of alternatives within that factor (i.e., factors must be chosen to avoid double-counting an advantage). If all alternatives have the same attribute for a given factor, that factor need not be considered. This example presents only factors with advantages. Another group of stakeholders or set of alternatives may warrant different factors.

STRUCTURAL ENGINEER'S FACTORS

Table 1 lists five factors (labelled SE-1 through SE-5) one specific structural engineer may consider when assessing a set of beam-column joint alternatives.

The factor **SE-1. Total cross-sectional area of rebar in column** refers to whether or not the area of rebar in the column satisfies the 'must' criterion set out in ACI-318. An engineer calculates the required rebar area for the column based on required tension strength for the column. Strength calculations include a strength reduction factor, φ (ranging from .65 to .90), to ensure design is conservative (i.e., column strength exceeds the applied loading). Thus, an engineer may try rebar configurations with less rebar than specified, as strength is likely higher than calculated. Following this logic, a column with 61.16 cm^2 of rebar is a viable alternative; although strictly-speaking ACI-318 requires 61.35 cm^2 of rebar for a column this size ('must' criterion).

The 'want' criterion expresses preference for minimizing the total rebar area to reduce material costs and minimize the reinforcement ratio. Minimizing the reinforcement ratio is thought to minimize congestion. However, in some cases, a smaller total area of rebar may not reduce congestion, as that configuration may include more small bars than one with a greater total area, and thus be more congested.

The factor **SE-2. Total cross-sectional area of rebar in top of beam** refers to whether or not the area of rebar in the top of the beam satisfies the 'must' criterion set out in ACI-318. If grade 420 rebar is used, this 'must' criterion requires at least 19.35 cm^2 of rebar be present in the top of the beam.

The 'want' criterion is to minimize total area.

The factor **SE-3. Spacing for concrete to bond to bars** refers to whether or not space between bars is sufficient for concrete to flow through, allowing bonding between the rebar and the concrete. To minimize slip between the concrete and the rebar, concrete needs to bond to as much rebar surface as possible.

The 'must' criterion states concrete must bond to rebar at some place in the joint. If the joint was made entirely of rebar, structural failure may occur, e.g., rebar alone may buckle under compressive loading, resulting in failure. However, concrete is strong in compression, so a joint with both rebar and concrete is less likely to fail under the same loading that would buckle rebar alone.

The 'want' criterion states more spacing is better, reflecting the engineer's preference for maximum bonding area.

The factor **SE-4. Lineal weight of rebar in joint** refers to the weight of rebar per meter of length in the joint. This factor contains only a 'want' criterion, which is to minimize weight, reflecting the engineer's preference to reduce material cost (rebar cost is often calculated per tonne, so according to this calculation, minimizing weight minimizes material cost) and weight of material to be placed. In some cases, a rebar fabricator may favour more weight if it makes placing easier.

Table 1: CBA Table for Rebar Configuration in Beam-Column Joint

FACTORS	ALTERNATIVES											
	Column 1, Beam 2		Column 1, Beam 3		Column 1, Beam 6		Column 2, Beam 2		Column 2, Beam 3		Column 2, Beam 6	
SE-1. Total cross-sectional area of rebar in column Must Criterion: Total rebar area in column >= 61.29 cm^2 Want Criterion: The least amount of rebar to fulfill must criterion is best												
Attributes:	61.94 cm^2		61.94 cm^2		61.94 cm^2		61.16 cm^2		61.16 cm^2		61.16 cm^2	
Advantages:							.78 cm^2 fewer	10	.78 cm^2 fewer	10	.78 cm^2 fewer	10
SE-2. Total cross-sectional area of rebar in top of beam Must Criterion: Total rebar area in column >= 19.35 cm^2 Want Criterion: The least amount of rebar to fulfill must criterion is best												
Attributes:	20.39 cm^2		19.35 cm^2		20.39 cm^2		20.39 cm^2		19.35 cm^2		20.39 cm^2	
Advantages:			1.04 cm^2 fewer	20					1.04 cm^2 fewer	20		
SE-3. Spacing for concrete to bond to bars Must Criterion: Concrete must be able to enter the beam-column joint Want Criterion: The more bar surface area that can bond to concrete, the better (more clear space between bars preferred)												
Attributes:	Intersection		Intersection		6.4 cm between beam and column reinforcement		Beam and column rebar touch, no intersection		6.1 cm between beam and column reinf.		Intersection	
Advantages:					6.4 additional cm of clear space	90	Beam and column do not intersect rather than intersect	55	6.1 additional cm of clear space	85		
SE-4. Lineal mass of rebar Want Criterion: The lighter the better												
Attributes:	73.9 kg/m		73.1 kg/m		73.9 kg/m		72.9 kg/m		72.1 kg/m		72.9 kg/m	
Advantages:			.8 kg/m less	15			1.0 kg/m less	20	1.8 kg/m less	45	1.0 kg/m less	20
SE-5. Maximum spacing between column bars Must Criterion: Concrete must be able to enter the beam-column joint (spacing must be at least as large as aggregate) Want Criterion: The more homogeneous, the better (lower maximum spacing is best)												
Attributes:	10.7 cm		10.7 cm		10.7 cm		14.5 cm		14.5 cm		14.5 cm	
Advantages:	3.8 cm less space	65	3.8 cm less space	65	3.8 cm less space	65						
F-1. Intersection of beam and column reinforcement Must Criterion: The bars of the column and the bars of the beam cannot intersect Want Criterion: The beam bars and column bars will touch, but not intersect												
Attributes:	Intersection		Intersection		6.1 cm between beam and column reinf.		Beam and column reinforcement touching, no intersection		6.1 cm between beam and column reinf.		6.1 cm between beam and column reinf.	
Advantages:					Bars do not touch or intersect	50	Bars touch rather than not touch	100	Bars do not touch or intersect	50	Bars do not touch or intersect	50
F-2. Number of bends necessary for beam and column bars not to intersect Want criterion: Fewer bends are better												
Attributes:	1 bend		2 bends		0 bends		0 bends		0 bends		0 bends	
Advantages:	1 bend fewer	10			2 bends fewer	25	2 bends fewer	25	2 bends fewer	25	2 bends fewer	25
F-3. Bar availability Must Criterion: Bars must be available for use as required by the placing schedule Want Criterion: Prefer to use bars with the shortest lead time												
Attributes:	#22 (#7) and #25 (#8) bar are readily available		#29 (#9) bar available in 2 weeks; others available		#29 (#9) bar available in 2 weeks; others available		#22 (#7) and #25 (#8) bar are readily available		#29 (#9) bar available in 2 weeks; others available		#29 (#9) bar available in 2 weeks; others available	
Advantages:	Material is most readily available	40					Material is most readily available	40				
F-4. Number of bars used Want Criterion: The less bars, the better												
Attributes:	23 bars		22 bars		18 bars		19 bars		18 bars		18 bars	
Advantages:			1 bar fewer	4	5 bars fewer	10	4 bars fewer	8	5 bars fewer	10	5 bars fewer	10
F-5. Number of layers of rebar in top of beam Must Criterion: At least one layer of reinforcement is required in the top of the beam Want Criterion: Fewer layers of reinforcement are preferred												
Attributes:	1 layer		1 layer		2 layers		1 layer		1 layer		2 layers	
Advantages:	1 less layer	5	1 less layer	5			1 less layer	5				
F-6. Number of different bar sizes used Want Criterion: Fewer different bar sizes is preferred												
Attributes:	2 sizes		2 sizes		3 sizes		2 sizes		3 sizes		3 sizes	
Advantages:	1 less size	5	1 less size	5			1 less size	5				
TOTAL IMPORTANCE:		125		114		240		268		245		115

The factor **SE-5. Maximum spacing between column bars** refers to the homogeneity of the material in the column. An element with more bars spaced closer together is more homogeneous than an element with one large bar, so the higher the maximum spacing, the less homogeneous the material. An engineer may focus more on homogeneity of material than on the number of bars used.

The 'must' criterion for this factor requires sufficient spacing for concrete to flow between bars. This is a function of aggregate size in the concrete mix (a design choice not determined within the scope of this example), but is on the order of 2 cm for this example (Mehta and Monteiro 2006). Homogeneity promotes better ductility and column behaviour, as forces distribute more evenly between bars. The 'want' criterion (the more homogeneous, the better) captures this preference.

REBAR FABRICATOR'S FACTORS

Table 1 also lists six factors (labelled F-1 through F-6) one specific rebar fabricator may consider when assessing the same set of beam-column joint alternatives.

The factor **F-1. Intersection of beam and column reinforcement** refers to whether or not beam and column reinforcement intersect if placed as specified. If plans show intersecting beam and column rebar, it must be bent or otherwise adjusted in the field to place it. If both beam and column reinforcement lie on the joint's centreline, rebar placers will adjust the beam or column bar to place the joint.

Although bars cannot physically intersect, intersection may be shown on plans. A 'must' criterion for this factor could state, "The bars coming into the joint cannot intersect." However, in most cases, if bars intersect on plans, one bar is moved, bent, or otherwise forced into place in the field, so this is not a 'must' criterion.

The 'want' criterion states the fabricator's preference for bars in the joint to be touching (not intersecting), thus eliminating the need to use spacers to place the joint.

The factor **F-2. Number of bends necessary for beam and column bars not to intersect** refers to the number of bends necessary to place rebar for the alternative as specified. The authors list attributes assuming a bar must be bent once to eliminate an intersection shown on plans (e.g., bar in the beam is bent to thread through column rebar). In reality, bars may not be bent in the field; instead they may simply be moved.

The 'want' criterion states preference for fewer bends; straight bars require less fabrication time.

The factor **F-3. Bar availability** refers to whether or not bars of a given size are available for use on the project. This factor accounts for the inventory of the fabricator and the lead time to get bars from the steel mill.

The 'must' criterion states that bars must be available for use when required by the rebar placing schedule.

The 'want' criterion states the fabricator's preference to use bars available sooner rather than later, as this allows placement to start earlier. Fabricators may keep a large inventory of bars, so they can provide bars for a job without long lead times. However, fabricators may not keep a large inventory of #43 [US #14] or #57 [US #18] bars, so if a job requires large quantities (> 110 tonnes) of either of these, the fabricator may coordinate with the mill to guarantee on-time rebar delivery (Richenberger 2008).

The factor **F-4. Number of bars** refers to the total number of bars to be placed.

The 'must' criterion states the total steel area must meet the ACI-318 requirement.

The 'want' criterion states that fewer bars are better because it is faster to place fewer bars; provided bars are not larger than #36 [US #11] (placing #43 [US #14] and #57 [US #18] bars requires a crane, so productivity rates decline from #36 [US #11] to #43 [US #14] to #57 [US #18]). Note rebar of any size or length may be placed with a crane. However, two ironworkers can manually lift bars smaller than #36 [US #11], but most cannot lift #43 [US #14] or #57 [US #18] bar (Bennion 2007).

The factor **F-5. Number of layers of reinforcement in top of beam** refers to the number of layers of reinforcement in the top of the beam for each alternative.

The 'must' criterion states the minimum requirement for layers of reinforcement, that is, one layer is necessary in the top of the beam to provide strength for the beam. In some cases, loading or concrete properties eliminate the need for rebar. However, alternatives considered in this example require rebar.

The 'want' criterion expresses the fabricator's preference for fewer layers of reinforcement to minimize the need for spacers to maintain a minimum distance between layers of rebar so as to allow concrete to go in-between.

SUMMARIZE ATTRIBUTES OF EACH ALTERNATIVE

Table 1 lists attributes of each alternative, each corresponding to a factor. In some cases, listing attributes may lead to consideration of new factors. For instance, when this example table was first developed, factors included 'Rebar area in beam' and 'Rebar area in column.' However, it became clear these factors were not specific enough, so 'Rebar area in beam' was split into 'Total cross-sectional area of rebar in top of beam' and 'Total cross-sectional area of rebar in bottom of beam.'

Attributes reflect data wherever possible. For example, within the 'Total cross-sectional area of rebar in top of beam' factor, the attributes of each alternative show calculations of total area. Listing facts or data as attributes makes the CBA process more transparent and defensible, as the basis for a decision is clear.

DETERMINE THE ADVANTAGES OF EACH ALTERNATIVE

Table 1 lists the dissimilarities or differences that make up the advantages of each alternative (Suhr 1999). Advantages reflect the backgrounds and expertise of the decision-makers who determine them. For instance, Table 1 reflects the authors' understanding of structural engineers' and fabricators' values.

ASSIGN A DEGREE OF IMPORTANCE TO EACH ADVANTAGE

When assigning a degree of importance to each advantage, first highlight the most-important advantage in each factor (Table 1).

Second, select the *paramount advantage*. To determine the paramount advantage, compare the most-important advantages in each factor and select the most-important of these most-important advantages (Suhr 1999). The paramount advantage is used to set the importance scale. The lowest importance is zero, which denotes 'no advantage.' The paramount advantage takes the highest spot on the importance scale. Usually, the paramount advantage is assigned an importance of 100; however, in some cases, the range of advantages may warrant another importance (i.e., 10 or 1,000). The paramount advantage in this case is 'Bars touch rather than not touch' in the factor 'F-1. Intersection of beam and column reinforcement,' given an importance of 100.

Third, weigh the importance of the most-important advantage in each factor, compared to the paramount advantage. Finally, assign a degree of importance to the remaining advantages relative to the most-important advantage in that factor and record it in the table (Table 1). Involving multiple stakeholders in assigning a degree of importance to advantages allows decision-makers to consider multiple viewpoints. Further, if all stakeholders are included in determining the importance of advantages, they can explain their decision (and defend it if necessary).

Team members may have competing values and may struggle to reach agreement about the importance of a given advantage. Different groups of stakeholders may decide on different importances for advantages.

CALCULATE TOTAL IMPORTANCE

Decision-makers total the importance of advantages of each alternative to identify the preferred alternative. The last row of Table 1 lists total importance for each alternative. Column 2 and Beam 2 (Total Importance = 268) is the preferred alternative.

CONCLUSIONS

CBA is a sound decision-making system that complements lean practices such as set-based design and early collaboration. The Tabular Method of CBA documents design and construction decisions, allowing new project team members to quickly become acquainted with alternatives considered and rationales used to evaluate these alternatives before they joined the team. This paper presents an example of the innovation and decision-making phases of a CBA process used to select rebar for a beam-column joint. The innovation phase consists of developing a set of alternatives (e.g., with set-based design) and determining the factors necessary to highlight the differences between these alternatives. The decision-making phase consists of choosing an alternative. During the decision-making phase, stakeholders assign a degree of importance to each advantage which spurs discussion among stakeholders about their values and preferences. This discussion can foster a shared understanding of the project goals and how each stakeholder contributes to realizing them. Once agreed upon, the table records the importance of each advantage.

This paper does not discuss the fourth and fifth phases of CBA, reconsideration and implementation. The reconsideration phase allows decision-makers to develop more alternatives or consider more factors if necessary (i.e., if the stakeholders are uncomfortable with the decision). The implementation phase applies the decision and makes adjustments if necessary during implementation.

Documenting alternatives, factors, criteria, attributes, advantages, and importances makes the decision-making process more transparent and provides a starting point for future decision-makers faced with a similar decision. As decisions begin to repeat from project to project, knowledge captured in CBA tables can be re-used, streamlining the decisions and decision-making process across projects.

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